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Influence of de-tuning and non-radiative recombination on the temperature dependence of 1.3 μm GaAsSb/GaAs vertical cavity surface emitting lasers

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In this letter, we measure the pure spontaneous emission and lasing emission from a working vertical cavity surface emitting laser (VCSEL) for a wide range of temperatures. From this spontaneous emission, we gain insight into the temperature dependence of the radiative component of the threshold current (and hence gain). Together with the temperature dependence of the threshold current, the cavity mode to gain peak alignment and the temperature dependence of an equivalent active region edge emitting laser, we show how non-radiative recombination coupled with gain-cavity de-tuning influences the thermal properties of these devices. © *2011 American Institute of Physics*. [doi:10.1063/1.3625938]

Vertical cavity surface emitting lasers (VCSELs) were originally proposed by Iga *et al.*[1] in 1977 and demonstrated in 1979.[2] Today, VCSELs can be found in many applications ranging from computer mice, short haul communications[3] through to oxygen sensors.[4] One particularly important potential application of VCSELs is in metropolitan area networks. Due to the zero dispersion and an absorption minimum of silica fiber available close to 1.3 μm, there has been significant effort devoted to producing VCSELs around this wavelength. Conventional edge-emitting lasers in this wavelength range are traditionally InP-based. However, the relatively small refractive index contrast between InGaAsP/InP alloys, compared to GaAs/AlGaAs, means that many multiples of layer pairs are required to produce the high reflectivity distributed Bragg reflectors (DBRs) as necessary for VCSEL operation, which can lead to both higher losses, higher operating voltages, and poorer thermal behavior. GaAs/AlGaAs DBRs have been used to produce 850 nm VCSELs for which InGaAs/GaAs quantum well (QW) active regions are also a mature technology. The challenge, therefore, has been to produce GaAs-based active regions providing operation around 1.3 μm. InGaAs/GaAs becomes very highly strained as the wavelength is pushed towards 1.3 μm, hence alternative approaches such as InAs/GaAs quantum dots[5] and GaInNAs/GaAs based QWs have been the subject of intensive studies. The properties of quantum dot lasers are far from ideal since their threshold current increases quickly with temperature. Explanations include non-radiative processes such as Auger recombination, gain saturation, or carrier excitation.[6] Quantum dot VCSELs at 1.28 μm have all recently been demonstrated.[7] 1.3 μm GaInNAs(Sb)-based QW VCSELs have been produced at 1.53 μm under pulsed excitation,[8] however, the material quality of dilute nitrides remains an issue.[9] Another possible GaAs-based system which has received less attention utilises GaAsSb/GaAs QWs.[10] GaAsSb-based edge emitting lasers and VCSELs close to 1.3 μm have both been produced with continuous wave (cw) operation at room temperature.[11,12]

One of the most important characteristics of a laser diode is its sensitivity to changes in the ambient temperature. Devices with low temperature sensitivity are desirable for commercial use by reducing their reliance on active temperature control which is expensive and significantly adds to the overall energy demands of the system. Due to their small size, self-heating exacerbates this issue in VCSELs. Long wavelength VCSELs have a complex temperature behavior due to the different material dependent recombination processes and the additional effect of the temperature dependent misalignment of the cavity mode wavelength (CM) with respect to the gain peak wavelength. In this paper, we quantify and separate these two effects and determine the extent to which they couple and govern the temperature dependent properties of GaAsSb/GaAs-based VCSELs. A key aspect of this study has been to measure the unamplified spontaneous emission (SE) from VCSELs during operation. From this, we have been able to observe carrier density pinning in the VCSELs above threshold and consequently used this to determine the intrinsic radiative component of the threshold current. Thus, we are able to directly observe the interaction of the VCSEL cavity with the material gain and its effect on the temperature dependence of the radiative and non-radiative processes occurring.

In this study, we investigated devices processed from wafers grown by solid source MBE. The QW region consists of three, 7 nm thick $GaAs_{0.64}Sb_{0.36}$ QWs with 5 nm GaAs barriers with the addition of GaAsP layers for strain compensation to ensure that the strain-thickness product is not exceeded. The 30 lower and 25 upper pairs of AlGaAs/GaAs DBRs, respectively, enclose a cavity length of 1.5 times the free space emission wavelength of 1.26 μm. The VCSELs were fabricated into devices with an oxide aperture and an optical window of 9 μm in diameter. Further details can be found in Refs. 12 and

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13. To minimize self-heating effects, devices were driven using 200 ns long pulses at a duty cycle of 10 kHz.

We begin by considering the temperature behavior of edge emitters with nominally the same active layer structure to probe the temperature dependence of the carrier recombination processes in the absence of the resonant VCSEL cavity. In order to do this, we have measured the threshold current and its radiative component (J_{rad}) in isolation. J_{rad} was measured by collecting the spontaneous emission through a transparent window milled into the substrate of the device using a focused ion beam technique.[14] Comparing the temperature dependence of the pure radiative current and the total threshold current density of 1.6 kA/cm^2, we found that more than 90% of J_{th} at room temperature in the edge-emitting lasers is due to non-radiative recombination, previously shown to be due to Auger recombination and leakage.[15]

In the VCSELs, the presence of a strongly wavelength dependent DBR reflectivity has a significant influence on the VCSEL device properties. In particular, the CM which determines the lasing wavelength of the VCSEL, red-shifts with increasing temperature at a much lower rate than the gain peak wavelength whose temperature dependence approximately follows the thermally induced band gap shift.[16,17] From measurements of the laser wavelength of edge emitting lasers, this is found to be 0.36 nm/K in agreement with calculations using the Varshni relation.[18] The change in the cavity mode is due to the much smaller change in the refractive indices of the semiconductor materials with temperature which comprise the Bragg reflectors, measured to be 0.07 nm/K. Hence, there is an optimum operating temperature where the CM aligns with the peak of the QW gain spectrum. In the absence of any other temperature dependencies in the device, the threshold current will be at a minimum close to this temperature since maximum gain is available at the cavity mode wavelength. As stated earlier, in the VCSEL, the lasing wavelength is principally determined by the cavity mode, whereas in the edge emitting laser, it is determined approximately by the gain peak wavelength. Comparing the temperature dependence of the CM and the gain peak wavelength provides an indication of the temperature at which the gain peak and cavity mode energies align.

Fig. 1 shows the temperature dependence of the peak lasing wavelength of an edge-emitting laser[11,15] and a VCSEL. Here, we assume that the temperature dependence of the lasing wavelength for the edge emitting laser (based on the same active region as the VCSEL) is equivalent to the temperature dependence of the gain peak for the VCSEL.

The temperature dependence of the VCSEL lasing wavelength also directly provides the temperature dependence of the cavity mode (for normal incidence). These data suggest that the gain-CM alignment occurs at a temperature of approximately 270($\pm$5) K. Confirmation of this comes from independent photomodulated reflectance spectroscopy results on unprocessed VCSEL wafer material.[19] In the comparison of the temperature dependence of the edge electroluminescence and the reflectivity (and thus the cavity mode), the alignment is found to occur at approximately 280($\pm$10) K. Further evidence for this comes from measuring the derivative of the reflectivity in temperature dependent electroreflectance measurements.[20] With this method, an alignment of the cavity mode and the QW electroluminescence have been found at

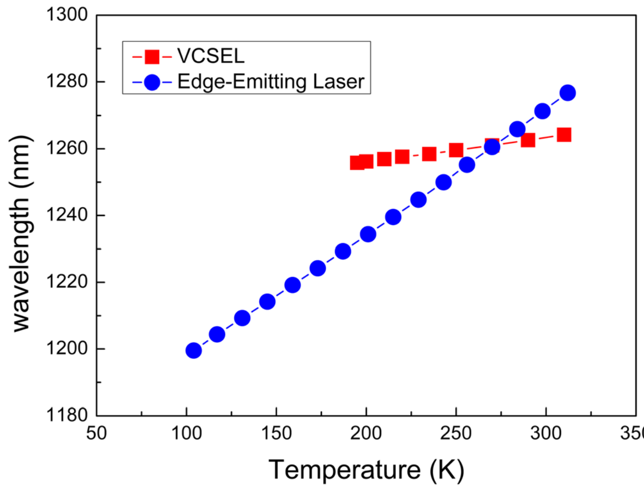

FIG. 1. (Color online) Temperature dependence of the lasing emission peak energy for a GaAsSb edge emitting laser (circles) and VCSEL (squares). The two lines intersect at $\sim$270 K, corresponding to gain cavity-mode alignment.

260($\pm$10) K. These data, therefore, suggest that the alignment occurs in the temperature range 260–280 K.

To investigate the temperature dependence of the VCSEL properties further, we measure both the lasing emission collected from the top of the device and the unamplified spontaneous emission as emitted from the side of the device. By measuring this at laser threshold, we can determine the temperature dependence of the threshold current and its radiative component. To measure the unamplified spontaneous emission from the VCSEL, the VCSEL wafer is cleaved close to the contact ring. The emitted light from the VCSEL is collected using two multi-mode silica optical fibres. One optical fibre collects the lasing emission from the top of the device while the second optical fibre, securely held $\sim$500 μm from the side of the device, simultaneously measures the unamplified spontaneous emission. The emission is measured as a function of both current and temperature (180-300 K) using a closed-cycle cryostat. Typical above threshold spectra measured from the top and side of the VCSEL are shown in Fig. 2(a) for a temperature of 210 K. It is clear that the side emission is much broader than the lasing emission consistent with it being unamplified SE. We also note that at this temperature, the VCSEL is "de-tuned" with the unamplified SE peak (gain peak) at a shorter wavelength than the VCSEL lasing wavelength (CM peak).

To find the radiative current (which is proportional to the SE), we find the intensity of the integrated SE at threshold. This intensity from the side together with the lasing emission at 210 K as a function of current is shown in Fig. 2(b). At threshold, pinning of the SE can be seen. This is as expected since the carrier density is clamped above threshold due to the lasing process. The intensity of the SE at threshold is measured for a range of temperatures. Since the integrated spontaneous emission is proportional to the radiative current, this, therefore, represents the temperature dependence of J_{rad}. To obtain J_{rad} in absolute units, it is assumed that, at low temperature, $J_{th} = J_{rad}$ (since non-radiative recombination is negligible at the lowest temperatures, as determined from edge-emitting laser studies) hence the integrated spontaneous emission is normalized to J_{th} at the lowest temperature, as shown

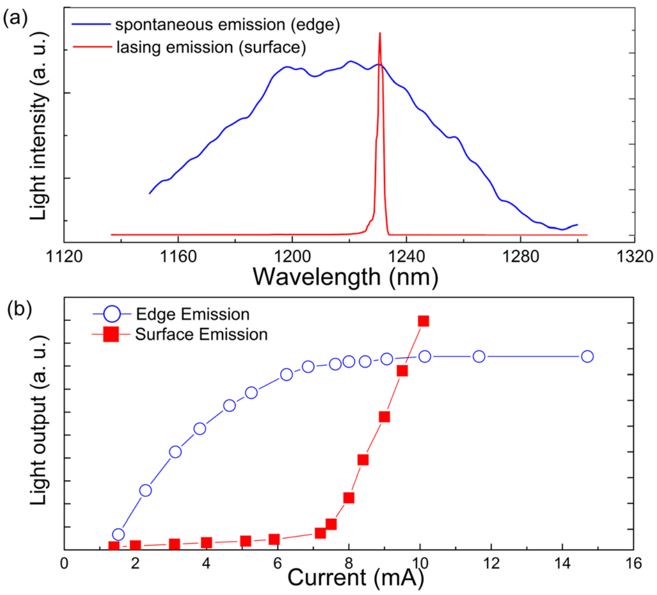

FIG. 2. (Color online) (a) Lasing emission and smoothed spontaneous emission spectra (at 210 K). The gain to cavity-mode misalignment is apparent from this graph. (b) Spontaneous emission (edge emission) together with the lasing emission (surface emission) for a VCSEL also at 210 K. The pinning of the spontaneous emission can be seen above threshold.

in Fig. 3. This provides a maximum value for J_{rad} (T). The fact that J_{rad} closely follows J_{th} in the low temperature range justifies this assumption.

At low temperature J_{rad} (open triangles in Fig. 3) is initially high. With increasing temperature, the gain red-shifts faster than the cavity mode (as shown in Fig. 2(a)) and J_{rad} decreases due to the increased gain at the cavity mode. This effect dominates over the typical linear increase in J_{rad} with temperature in a QW.[14] At low temperature J_{th} (filled circles in Fig. 3) follows J_{rad} with a minimum at 225 K since here $J_{th} \approx J_{rad}$. The fact that J_{th} increases above 225 K, while J_{rad} continues to decrease (due to improved gain-cavity alignment), indicates the presence of non-radiative recombination at the higher temperatures (shaded area in Fig. 3). The source of the non-radiative current is likely to be due to a combination of Auger recombination and leakage, as found from previous pressure and temperature dependence studies on edge-emitting lasers based upon the same active region.[15]

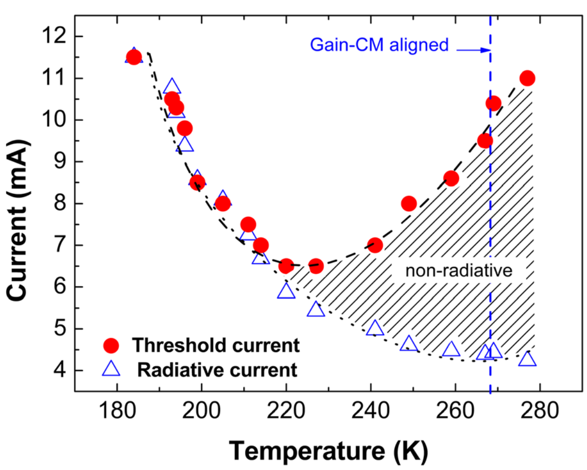

FIG. 3. (Color online) Temperature dependence of I_{th} and I_{rad} in the VCSEL. The decrease in J_{th} and J_{rad} with increasing temperature in the low temperature range is due to gain to cavity-mode tuning. Non-radiative recombination causes the increase in J_{th} with temperature above ~230 K and can be seen as the increase in the shaded area.

At 280 K based upon these data, we estimate that the non-radiative recombination accounts for at least 60% of J_{th} compared to the almost 90% measured for the edge emitter at this temperature. In order to achieve a flat temperature dependence around room temperature in these devices, a design where the gain and cavity-mode align at higher temperature (>300 K) would be preferable, as the tuning-effect close to room temperature could, at least partially offset the increase in non-radiative current with increasing temperature and is the subject of ongoing investigations.[21]

In conclusion, we have experimentally measured the temperature dependence of the radiative current in a working VCSEL. Together with the temperature dependence of the threshold current of the VCSEL, this has allowed us to determine and quantify the influence of non-radiative recombination on VCSEL performance. These results clearly illustrate the importance of accounting for non-radiative recombination as well as de-tuning when designing a VCSEL for temperature stable operation around room temperature.

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